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HUMAN HEAD LINEAR AND ANGULAR ACCELERATIONS DURING IMPACT

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13. ABSTRACT

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The results indicated that peak head angular and linear resultant accelerations were elevated with the air bag in contrast to the Air Force shoulder harness or lap belt only restraints. However, the peak angular and linear accelerations may have less traumatic consequences than the degree of head-neck hyperextension.

PREVIOUS RESEARCH HAS REVEALED the favorable impact protection afforded by the air bag (1,2).** However, at their present stage of development, air bags involve greater uncertainty and risk than restraints previously introduced in the auto safety field (3). Of particular concern is whether the restraining force of the air bag may result in exceeding human tolerance limitations of the head-neck. In this report the objectives were to determine head linear accelerations plus angular accelerations, velocities and displacements during exposure to abrupt linear deceleration ($-G_x$) while restrained with a lap belt only, standard Air Force shoulder harness or air bag plus lap belt. Correlation of the acceleration, velocity and displacement values with human subject response and trauma will be discussed.

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MATERIALS AND METHODS

Thirty-six deceleration tests were performed with 14 adult male volunteers. Peak sled velocities ranged from 23.1 to 27.2 ft/sec resulting in maximum sled decelerations of 7.7 to 10.3 g. The impact pulse was approximately half sine with a stopping distance of 2 ft. Air bag inflation was mechanically activated at the initiation of the sled deceleration pulse.***

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*The voluntary informed consent of the subjects used in this research was obtained as required by Air Force Regulation 169-8.

**Numbers in parentheses designate references at end of paper.

***The air bag systems were gratuitously provided by Eaton, Yale and Towne, Inc.

A low-pass filter (100 Hz) improved the legibility of the acceleration traces with no appreciable loss of response (1,2).

Previous investigators (4) computed head angular accelerations via numerical differentiations of photographically derived angular displacement curves. However, envelopment of the head by the air bag precluded this type of analysis (Fig. 1).

Biaxial accelerometer clusters were affixed to anterior and posterior flanges of a lightweight plastic head mount. The mount, restraining straps and accelerometers weighed 11.3 oz (Fig. 2). The design of the angular acceleration system is dependent upon the principle that the tangential acceleration of point A on a rigid body relative to point B on the body, divided by their separation distance, is the angular acceleration of the body within a spatial reference system (5). Only the rotation in the sagittal plane or about the lateral axis of the head (pitch) is described. Integration of head angular accelerations yielded head angular velocity. Angular displacement of the head was computed by an additional integration. Front and rear linear accelerations were computed by vector summation of the X and Z components of the anterior and posterior accelerometer clusters.

RESULTS AND DISCUSSION

The head reference axes are depicted using a polar coordinate system where angular displacement of the head was positive with flexion and negative with hyperextension.

LAP BELT RESTRAINT - Head angular acceleration, velocity and displacement of a human restrained with only a lap belt are graphically displayed for a 9.2 g impact (Fig. 3).

For all tests the excursions of the accelerometer data correspond closely in magnitude and time phase. The head angular acceleration trace was typically biphasic in shape. The positive peak normally occurred 160 milliseconds after time zero. Twenty to 50 milliseconds later the acceleration trace reached the maximum negative value. The positive peak was invariably greater in magnitude than the negative excursion (Table 1). The trace returned to zero by 350 ms.

The head angular velocity trace was primarily positive and therefore the maximum negative value was excluded from Table 1. The head angular displacement curve was invariably positive. This was indicative that the head-neck only underwent flexion. It should be emphasized that the zero position of the head was the actual position of the head at time zero and not necessarily the neutral anatomical position (head erect). However, the head at time zero never exceeded 15 degrees positive or negative from the neutral anatomical position.

Although the head angular displacement trace remained at zero for at least the first 100 ms of the impact event, the head was translating forward with the torso in a linear manner. The maximum head angular displacement occurred at approximately 300 ms. While the mean angular displacement of the head was 103 degrees (Table 1), the extent of head-neck flexion with respect to the torso never exceeded 50 degrees.

The linear resultants (Fig. 4) of the front and rear accelerometer clusters peaked at approximately the same time of the head angular acceleration excursions (Fig. 3). It should be noted that Fig. 3 shows the coplanar vector representation of the front and rear accelerometers and not necessarily the acceleration of the center of gravity of the head. The maximum linear acceleration was invariably recorded with the front accelerometer cluster.

AIR FORCE SHOULDER HARNESS RESTRAINT - The head angular acceleration, velocity and displacement traces when restrained with an Air Force shoulder harness (Fig. 5) displayed close similarity to the previously discussed lap belt traces (Fig. 3). The major dissimilarity was the shorter duration from time zero to the initiation of the excursions.

The mean peak angular accelerations and decelerations while restrained with the Air Force shoulder harness (Table 2) were less than restrained with the lap belt (Table 1), even though the mean sled deceleration with the shoulder harness was slightly higher than comparable tests using the lap belt only.

The mean head angular displacement with the Air Force shoulder harness was 75 degrees. However, since the torso was restrained and never rotated foreward more than 20 degrees from the erect position, the extent of head-neck flexion with respect to the torso was greatest with this restraint. With this extent of head-neck flexion the subject's mandible often contacted the sternum. Previous researchers have found the maximum angle of flexion to be 53 degrees (6).

The peak linear accelerations were slightly less when restrained with the shoulder harness (Table 2). The peak excursions occurred at the same time as the peak head angular accelerations (Fig. 6).

AIR BAG PLUS LAP BELT RESTRAINT - From 60 to 70 ms the rapid excursions of the head acceleration trace were primarily attributable to bag contact with the thorax and head (Fig. 7). The negative spike near 80 ms averaged -178,200 degrees/sec^2 (Table 3) and was invariably the maximum head angular deceleration. The duration of this spike was much shorter than the subsequent positive and negative peaks. The positive head angular acceleration peak was extremely inconsistent in magnitude and often of inconsequential value.

The head angular displacement curve was invariably negative indicating that the head only underwent hyperextension after time zero. Although the mean peak negative rotation of the head was 42 degrees, the longitudinal axis of the torso displaced forward 10 to 20 degrees from vertical. Likewise, the head during many of the tests was hyperextended 15 degrees from the neutral anatomical position at time zero. Therefore, at 180 ms the actual head-neck hyperextension relative to the torso for a specific test may average -77 degrees or only 2 degrees less than the mean voluntary limit of hyperextension (6). This pronounced hyperextension of the head-neck was attributable to the restraining force of the air bag. In essence, the air bag was sufficient to overcome the forward momentum of the head to a much greater extent than the torso of larger mass.

In five tests with the air bag the peak linear resultants of the front and rear accelerometer clusters exceeded 70 g for a cumulative duration of more than 3 ms. These head accelerations were not appreciably lower than the proposed quantitative occupant injury criteria for a 30 mph barrier impact using anthropomorphic test devices (7). The higher readings of the front accelerometer cluster may be in part due to bag "slap" (Fig. 8).

Although there was no evidence of definitive whiplash injury, six subjects restrained with the air bag plus lap belt developed mild to moderate headaches from 2 to 24 hours post-impact (Table 4). This appears to be related to the degree of head-neck hyperextension since headaches resulted with only the subjects who experienced the greatest degree of hyperextension. Furthermore, the subject with the most severe headache underwent the greatest head-neck hyperextension.

No correlation was found between headache and angular or linear accelerations.

CONCLUSIONS

The results indicated that peak head angular accelerations and linear resultants were elevated with the air bag in contrast to the Air Force shoulder harness or lap belt only restraints. However, the angular and linear accelerations may have less traumatic consequences than the degree of head-neck hyperextension.

ACKNOWLEDGMENT

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APPENDIX

OBJECT - The measurement of linear accelerations at two points on the head will yield after calculations absolute or total angular accelerations of the head with respect to a non-rotating spatial reference system.

LIMITATIONS - The angular accelerations of the head with respect to the neck or torso are not being derived. The angular accelerations, velocities and displacements of the head are only in the sagittal plane (pitch). There was no evidence of lateral head rotation (roll or yaw) from the high-speed film.

GOVERNING EQUATIONS AND CALCULATIONS -

Graphical Computation - Given a subject at time zero referenced to the X-Z coordinate system (Fig. 9). The head of the subject is defined by two points A and B which contain accelerometers aligned along the +X and +Z axes. The points are separated by the length L which is of constant value.

After a time "t" the head of the subject has rotated from the original position (Fig. 10). This is represented by line AB which has rotated through an angle θ (Fig. 11). Likewise, the accelerometers have rotated through the same angle θ and the rotated axes are designated by X' and Z'.

The accelerometers at A and B measure the instantaneous coplanar accelerations of each point which are typically represented by vectors as shown in Fig. 12.

The relative acceleration of point A relative to point B is obtained with the vector equation:

$$\mathbf{a}_{A/B} = \mathbf{a}_{A} - \mathbf{a}_{B} \tag{1}$$

Since the line AB is fixed in length then the relative acceleration of $\mathbf{a}_{A/B}$ can be broken into its normal and tangential components of $\mathbf{a}_{A/B(N)}$ and $\mathbf{a}_{A/B(T)}$. These components are parallel and perpendicular to the line AB, respectively (Fig. 13).

By definition the magnitudes of coplanar rotation components are:

$$a_{A/B(N)} = -L\dot{\theta}^2 \tag{2}$$

$$a_{A/B(T)} = -L\ddot{\theta} \tag{3}$$

where $\dot{\theta}$ and $\ddot{\theta}$ are the angular velocity and angular acceleration respectively.

It is observed that the magnitude of $\mathbf{a}_{A/B(T)}$ is the difference between the Z' components of $\mathbf{a}_A$ and $\mathbf{a}_B$ or

$$a_{A/B(T)} = a_{AZ'} - a_{BZ'} = -L\ddot{\theta} \tag{4}$$

Thus

$$\ddot{\theta} = \frac{a_{BZ'} - a_{AZ'}}{L} \tag{5}$$

Where R(1) and R(2) are the readings of the front and rear Z accelerometers respectively:

$$\ddot{\theta} = \frac{R(2) - R(1)}{L} \tag{6}$$

or

$$\ddot{\theta} = \frac{a_{rear\ Z} - a_{front\ Z}}{L} \tag{7}$$

Vector Computation - A compatible vector representation of the coplanar motion can be achieved by using Fig. 14. The X and Z axes are defined as positive to the left and upward, respectively. Using the left handed rule, the Y axis is directed into the paper. This reference system, then, is compatible with the series of photographs of the tests.

Mathematically, the motion of line AB may be referenced to a translating reference system with origin at B. Points A and B contain the accelerometers. For this development the unit vector $\mathbf{i}$ is directed along the X axis, the unit vector $\mathbf{j}$ along the Y axis and the unit vector $\mathbf{k}$ along the Z axis. $\mathbf{r}$ is the vector representing the distance AB. The general components of the vector $\mathbf{r}$ are taken as:

$$\mathbf{r} = r_X \mathbf{i} + r_Z \mathbf{k} = \mathbf{r}_A - \mathbf{r}_B \tag{8}$$

Since the magnitude of $\mathbf{r}$ is constant, the relative velocity of point A with respect to point B represents the rotational motion of line AB. Thus, the following results:

$$\mathbf{v}_{A/B} = \frac{d\mathbf{r}}{dt} = r_X \frac{d\mathbf{i}}{dt} + r_Z \frac{d\mathbf{k}}{dt} = \boldsymbol{\omega} \times \mathbf{r} \tag{9}$$

where

$$\boldsymbol{\omega} = \dot{\theta}\,\mathbf{j}$$

The acceleration of point A relative to point B is defined as:

$$\mathbf{a}_{A/B} = \frac{d\mathbf{v}_{A/B}}{dt} = \boldsymbol{\omega} \times \frac{d\mathbf{r}}{dt} + \frac{d\boldsymbol{\omega}}{dt} \times \mathbf{r} \tag{10}$$

where

$$\frac{d\mathbf{r}}{dt} = r_X \frac{d\mathbf{i}}{dt} + r_Z \frac{d\mathbf{k}}{dt} = \boldsymbol{\omega} \times \mathbf{r} \tag{11}$$

$$\frac{d\boldsymbol{\omega}}{dt} = \dot{\theta}\frac{d\mathbf{j}}{dt} + \frac{d\dot{\theta}}{dt}\,\mathbf{j} \tag{12}$$

Since the axis J does not rotate $\frac{d\mathbf{j}}{dt} = 0$

Thus,

$$\frac{d\boldsymbol{\omega}}{dt} = \boldsymbol{\alpha} = \frac{d\dot{\theta}}{dt}\,\mathbf{j} = \ddot{\theta}\,\mathbf{j} \tag{13}$$

Finally,

$$\mathbf{a}_{A/B} = \boldsymbol{\omega} \times (\boldsymbol{\omega} \times \mathbf{r}) + \boldsymbol{\alpha} \times \mathbf{r} = \mathbf{a}_A - \mathbf{a}_B \tag{14}$$

The vector $\boldsymbol{\omega} \times (\boldsymbol{\omega} \times \mathbf{r})$ is directed along the line AB and represents the relative normal acceleration $\mathbf{a}_{A/B(N)}$. The vector $\boldsymbol{\alpha} \times \mathbf{r}$ is directed perpendicular to line AB and represents the relative tangential acceleration $\mathbf{a}_{A/B(T)}$. The X′-Z′ coordinate system (Fig. 10) also defines these normal and tangential components. Accelerometers numbered (1) and (2) (Fig. 14) measure the Z′ components of the accelerations of A and B which can be represented by:

$$\mathbf{a}_{A/B(T)} = \mathbf{a}_{AZ'} - \mathbf{a}_{BZ'} \tag{15}$$

In scalar form

$$a_{A/B(T)} = -r\ddot{\theta} = a_{AZ'} - a_{BZ'} \tag{16}$$

$$\ddot{\theta} = \frac{a_{BZ'} - a_{AZ'}}{r} \tag{17}$$

$$\ddot{\jmath} = \frac{a_{\text{rear } Z} - a_{\text{front } Z}}{r} \tag{18}$$

Table 1 - Lap Belt Restraint (10 Subjects)

	A	B	C	D	E	F	G	H
Mean	+45,700	-29,500	+1012	-	22	14	+103	9.4
S. D.	±20,500	±11,300	±182	-	±7	±5	±10	±0.3

A = Maximum head angular acceleration (deg/sec^2)
B = Maximum head angular deceleration (deg/sec^2)
C = Maximum positive head angular velocity (deg/sec)
D = Maximum negative head angular velocity (deg/sec)
E = Maximum front head linear acceleration (g)
F = Maximum rear head linear acceleration (g)
G = Maximum flexion of head-neck from position at time zero (deg)
H = Maximum sled deceleration (g)
- = Highly inconsistent or of minimal value

Table 2 - Air Force Shoulder Harness Restraint (12 Subjects)

	A	B	C	D	E	F	G	H
Mean	+31,800	-25,500	+1060	-	20	12	+75	9.6
S. D.	±14,500	±7,900	±290	-	±6	±2	±20	±0.4

A = Maximum head angular acceleration (deg/sec^2)
B = Maximum head angular deceleration (deg/sec^2)
C = Maximum positive head angular velocity (deg/sec)
D = Maximum negative head angular velocity (deg/sec)
E = Maximum front head linear acceleration (g)
F = Maximum rear head linear acceleration (g)
G = Maximum flexion of head-neck from position at time zero (deg)
H = Maximum sled deceleration (g)
- = Highly inconsistent or of minimal value.

Table 3 - Air Bag Plus Lap Belt Restraint (14 subjects)

	A	B	C	D	E	F	G	H
Mean	-	-178,200	-	-1027	71	55	-42	8.9
S. D.	-	±38,900	-	±125	±17	±7	±16	±0.6

A = Maximum head angular acceleration (deg/sec^2)
B = Maximum head angular deceleration (deg/sec^2)
C = Maximum positive head angular velocity (deg/sec)
D = Maximum negative head angular velocity (deg/sec)
E = Maximum front head linear acceleration (g)
F = Maximum rear head linear acceleration (g)
G = Maximum hyperextension of head-neck from position at time zero (deg)
H = Maximum sled deceleration (g)
- = Highly inconsistent or of minimal value.

Table 4 - Correlation of Hyperextension and Headache

Subject	Extent of Head-Neck Hyperextension	Severity of Headache
1	-69°	******
2	-61°	*****
3	-58°	****
4	-56°	***
5	-53°	*
6	-47°	**

* least severe headache - ****** most severe headache

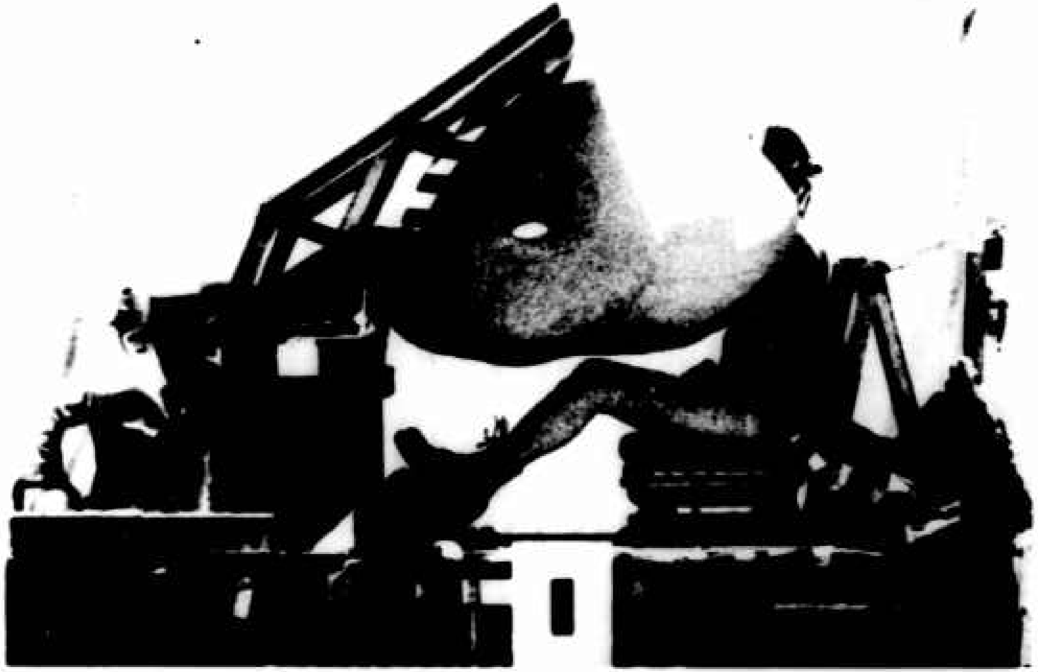

Fig. 1 - Partial envelopment of head by air bag

Fig. 2 - Test subject with accelerometer head mount

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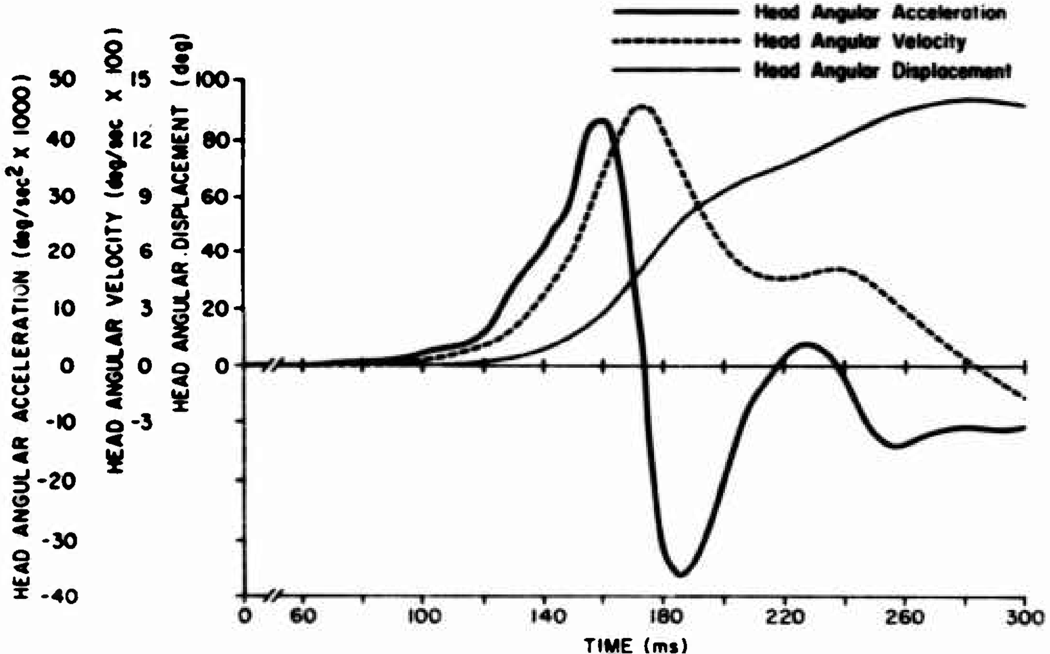

Fig. 3 - Head angular acceleration, velocity and displacement versus time. Lap belt restraint at 9.2 g. Run No. 4931, subject No. 1

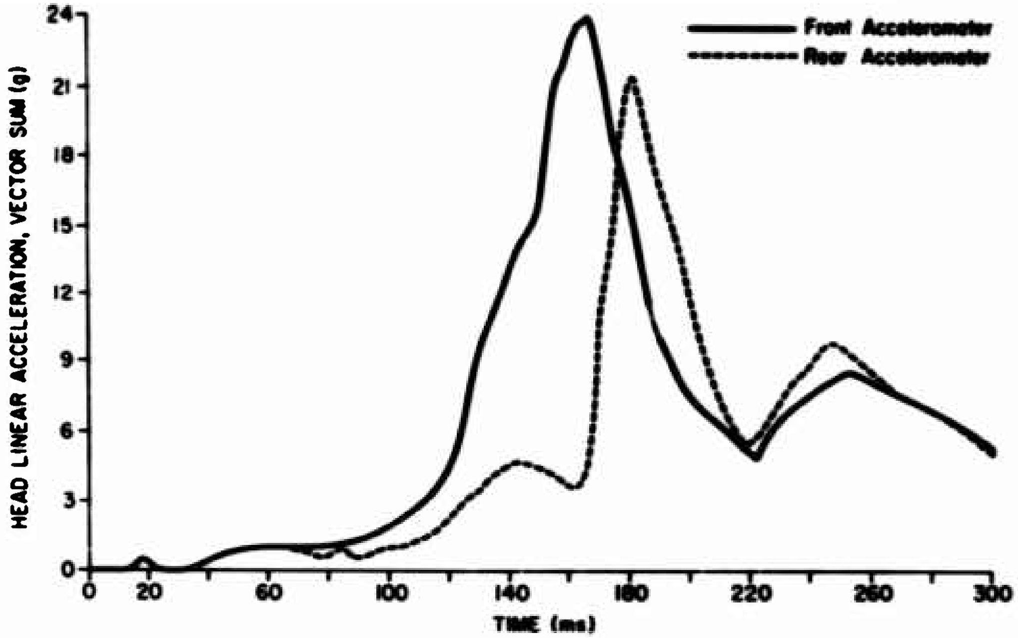

Fig. 4 - Head linear acceleration versus time. Lap belt restraint at 9.2 g. Run No. 4931, subject No. 1

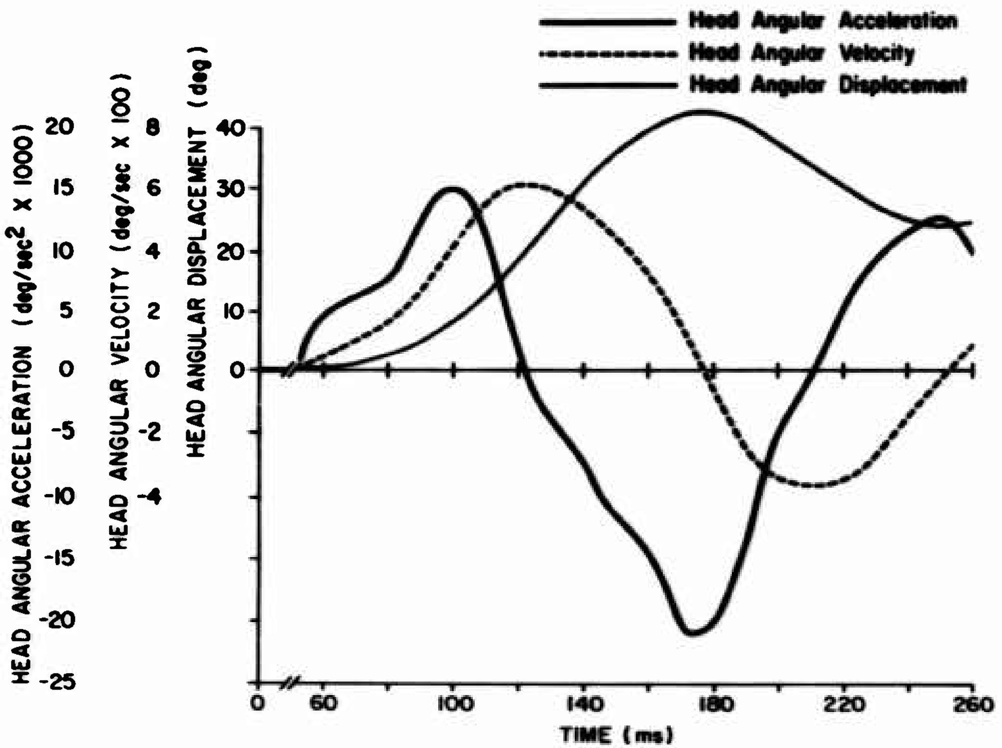

Fig. 5 - Head angular acceleration, velocity and displacement versus time. Shoulder harness restraint at 9.5 g. Run No. 4949, subject No. 1

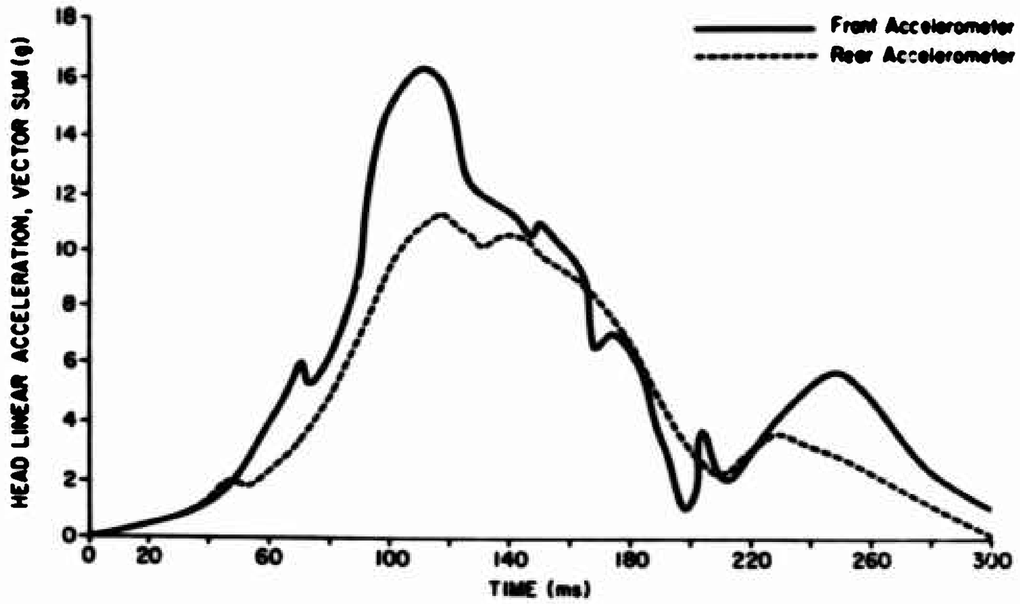

Fig. 6 - Head linear acceleration versus time. Shoulder harness restraint at 9.5 g. Run No. 4949, subject No. 1

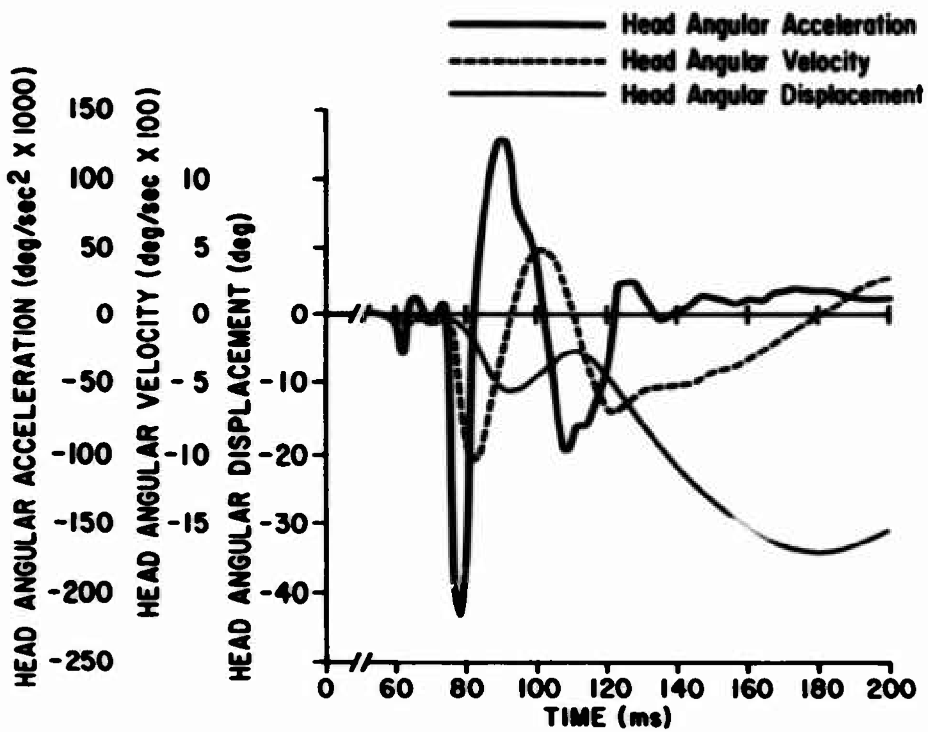

Fig. 7 - Head angular acceleration, velocity and displacement versus time. Air bag and lap belt restraint at 8.4 g. Run No. 4821, subject No. 1

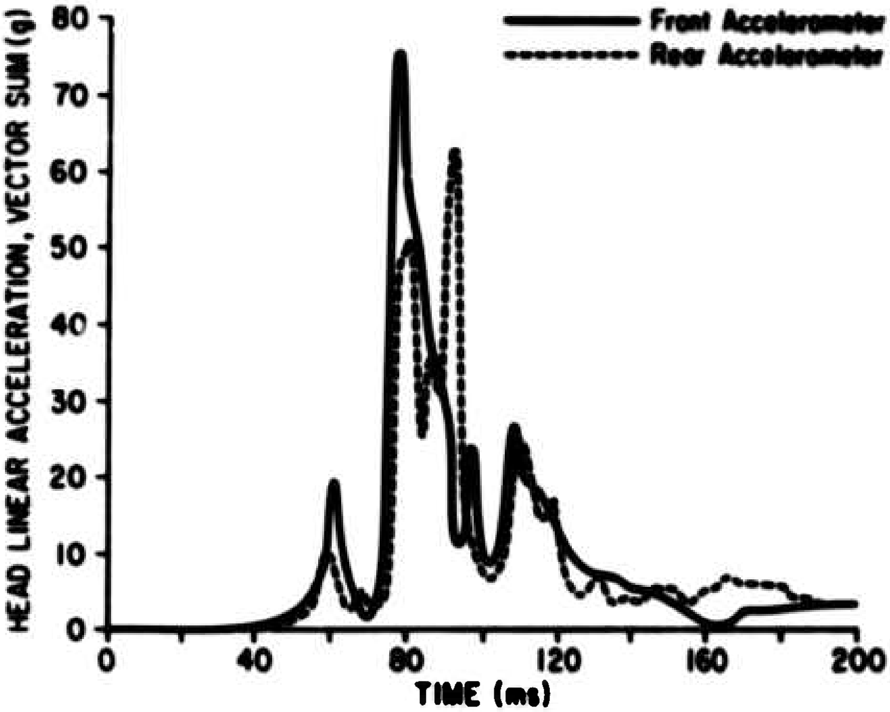

Fig. 8 - Head linear acceleration versus time. Air bag and lap belt restraint at 8.4 g. Run No. 4821, subject No. 1

Fig. 10 - Time: 0 - t

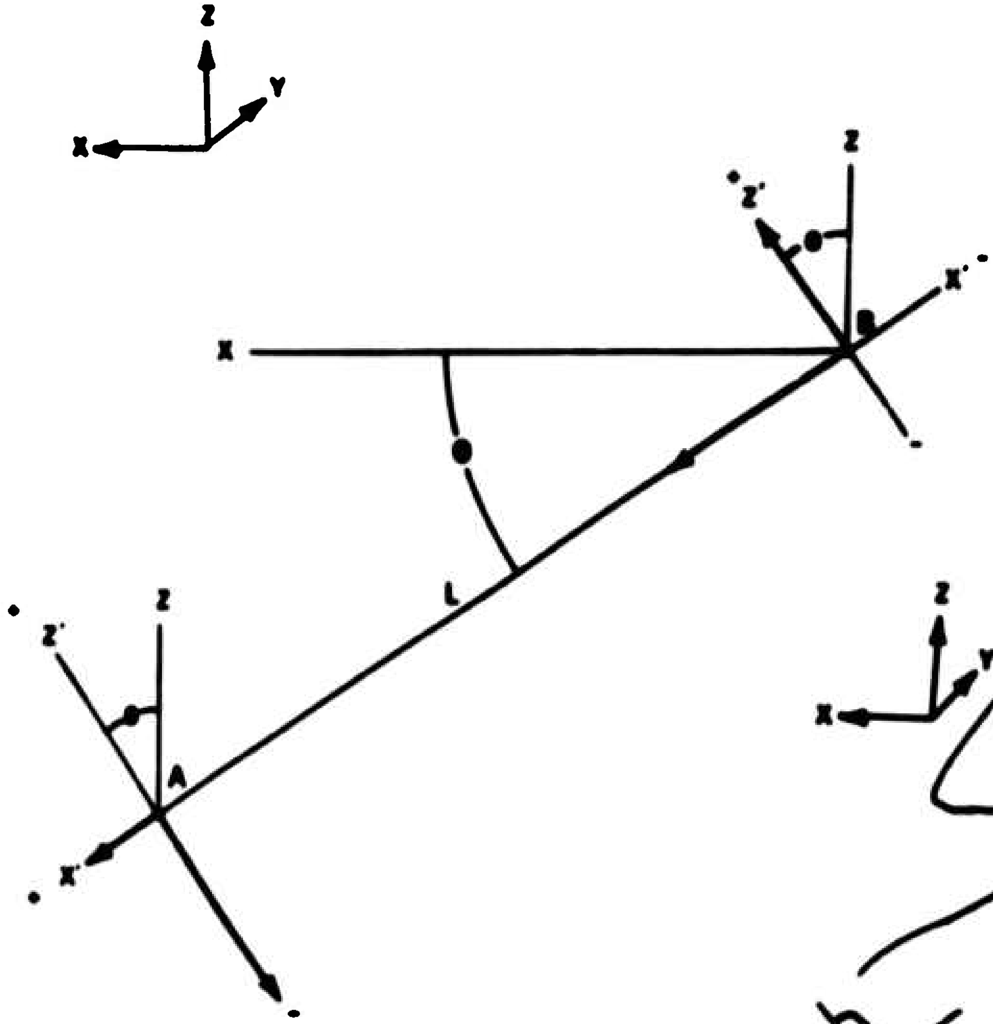

Fig. 11 - Time: 0 - t

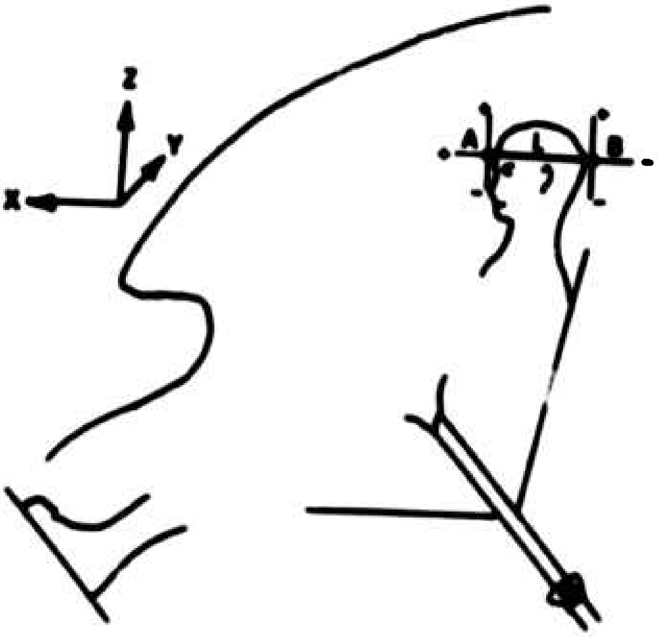

Fig. 9 - Time: 0

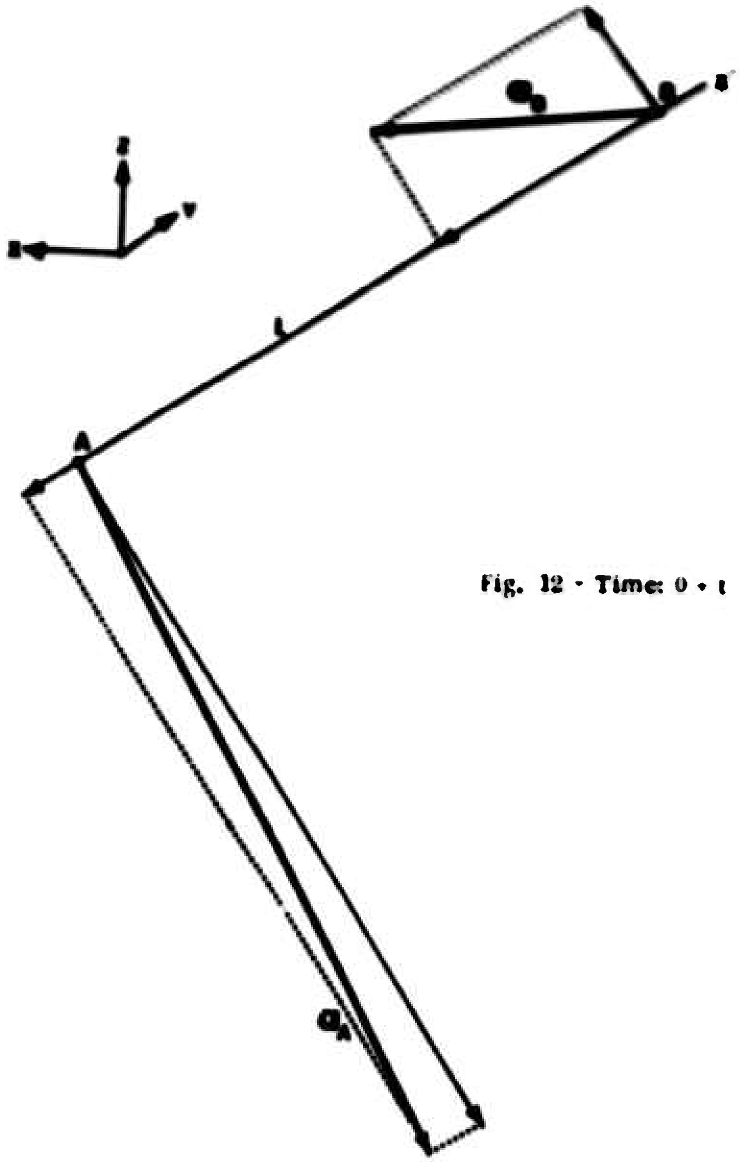

Fig. 12 - Time: 0 + t

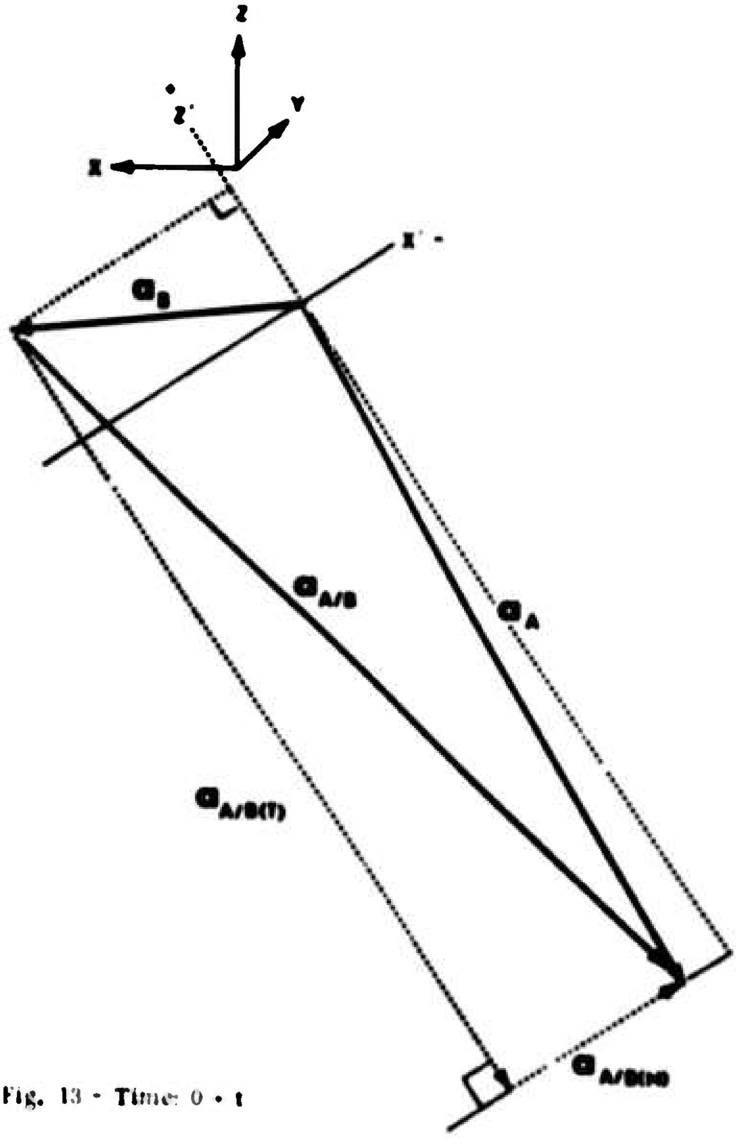

Fig. 13 - Time: 0 + t

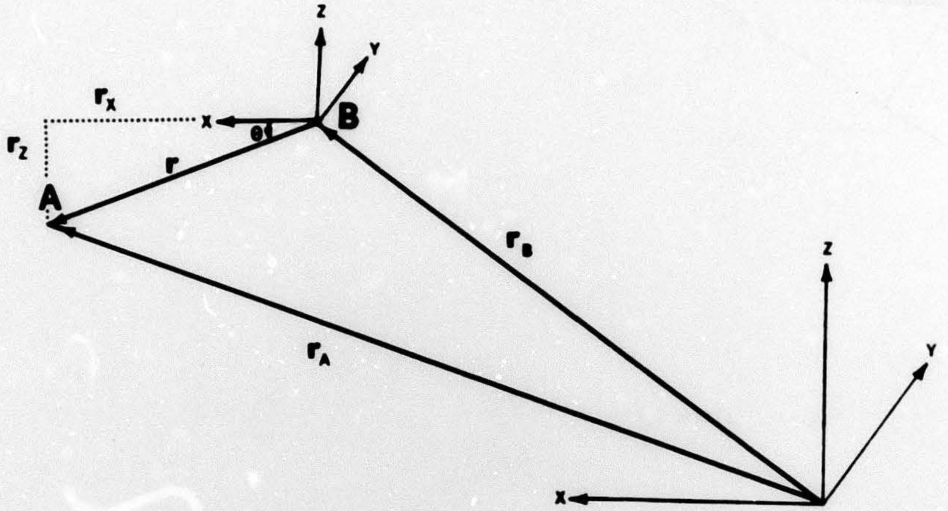

Fig. 14 - Time: 0 + t

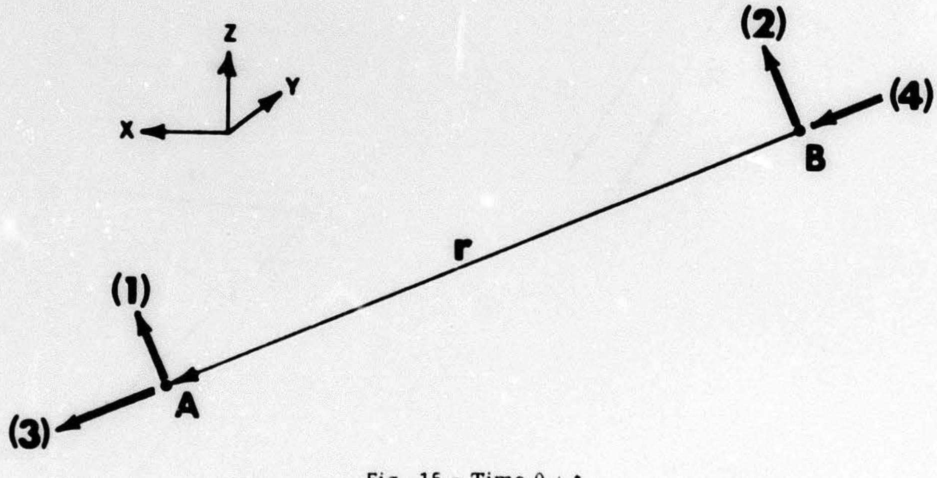

Fig. 15 - Time 0 + t

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